(Preprint) AAS 17-596

CASSINI MANEUVER EXPERIENCE THROUGH THE FINAL TARGETED TITAN FLYBY AND THE GRAND FINALE

Sean V. Wagner[*], **Yungsun Hahn**[†], **Sonia Hernandez**[†], **Frank E. Laipert**[†], **Powtawche N. Valerino**[†], **Mar Vaquero**[†], **and Mau C. Wong**[†]

Jet Propulsion Laboratory, California Institute of Technology

Amassing valuable scientific information about the Saturnian system for 13 years, the Cassini spacecraft is now in the last phase of its mission. The Grand Finale, a series of 22 orbits with Cassini passing through a gap between Saturn's innermost ring and its upper atmosphere, began after the last targeted Titan flyby on April 22, 2017 and ends with the spacecraft plunging into Saturn on September 15, 2017. This paper reports on the maneuvers performed to achieve the final targeted Titan encounter and the maneuvers used to maintain the Grand Finale orbits.

INTRODUCTION

After nearly 20 years in flight, the Cassini spacecraft has now reached the last phase of its mission at Saturn. Beginning after the last targeted Titan encounter on April 22, 2017, the Grand Finale is the final phase of the Cassini Solstice Mission. It consists of 22 highly-inclined and short-period ballistic orbits around Saturn, where near periapsis, Cassini passes through a 2,550 km gap between Saturn's inner D-ring and the upper atmosphere.[1] After completing the 22 orbits, the spacecraft will then journey into Saturn's atmosphere on September 15, 2017 (see Figure 1). In addition to properly disposing the Cassini spacecraft, the Grand Finale presents a unique opportunity for scientists to further study the Saturnian system from a new perspective.

The Cassini mission at Saturn has been accomplished mainly through gravity assists from Titan and the icy satellites with propulsive maneuvers designed by the Cassini Navigation Team. Cassini executes maneuvers by using two independent propulsion systems for trajectory corrections: the bi-propellant Main Engine Assembly (MEA) for performing large burns and the Reaction Control System (RCS) thrusters for small burns. The spacecraft has performed a total of 360 maneuvers: 183 with the main engine and 177 with the RCS thrusters. Earlier papers by members of the Cassini Maneuver Team reported on the maneuvers performed during the seven-year interplanetary cruise,[2–4] the four-year Prime Mission,[5–8] the two-year Equinox Mission,[9,10] and the first six years of the Solstice Mission.[11–16] This paper documents the seven Orbit Trim Maneuvers, OTMs 467–472, that were performed over a seven-month period from December 2016 to July 2017, as well as three contingency maneuvers, OTMs 473–475, scheduled between August 17 and September 5, 2017. The

[*]Corresponding Author, member of the Flight Path Control Group and the Cassini Navigation Team, *Mailing Address*: Jet Propulsion Laboratory, Mail Stop 230-110, 4800 Oak Grove Drive, Pasadena, CA 91109; *Tel*: (818) 393-5972; *Fax*: (818) 393-4215; *E-mail address*: Sean.V.Wagner@jpl.nasa.gov

[†]Authors are members of the Flight Path Control Group and the Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

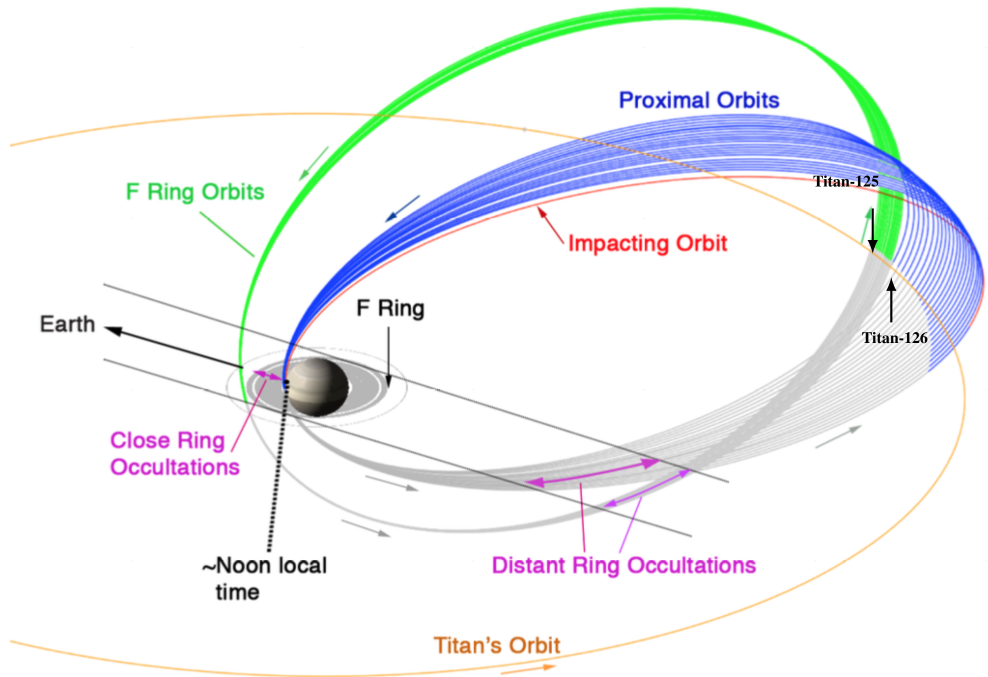


Figure 1: Schematic of the Cassini Grand Finale (Proximal Orbits) in blue and the F-Ring Orbits in green. *The final impacting orbit is depicted in red.*

first four of these maneuvers (OTMs 467, 468, 468a, and 469) achieved the desired conditions for the final targeted Titan flyby on April 22, 2017 and satisfied spacecraft planetary protection requirements, guaranteeing spacecraft disposal in Saturn's atmosphere. The next three maneuvers (OTMs 470, 471, and 472) enabled a rich collection of science data by keeping the spacecraft near the reference trajectory used to design the observations. Finally, the last three maneuvers (OTMs 473, 474, and 475) are contingency maneuvers that may or may not be performed. Based on assessments by the Cassini mission planners, these maneuvers will either raise or lower periapsis to provide better measurements of the Saturn atmosphere during the last five revolutions of the Grand Finale. During the transfer between the last two targeted Titan flybys, Titan-125 (T125) and Titan-126 (T126), the ring plane crossing radius was just outside the edge of Saturn's F-ring with a period of seven days and an inclination over 60°. These F-ring orbits, as seen in Figure 1, involved the spacecraft completing 20 orbits over a time period of approximately 142 days enabling close-in, low solar phase ring observations crucial to many ring science objectives.[17] This was in preparation for the final 'hop' over the main rings for the Grand Finale orbits when the period was further reduced to 6.5 days. This F-ring orbits phase also served as a dress rehearsal for the type of operations expected during the Grand Finale.

MANEUVER AND ENCOUNTER SUMMARY

Figure 2 shows a diagram of the maneuvers and other major Navigation events between T125 and Saturn impact on September 15, 2017. The events are ordered by increasing orbit number around Saturn from top to bottom, with the true anomaly of the event indicated by its horizontal position. The period of each orbit is noted along the right-hand side. The reference trajectory times for each of the 22 periapses during the proximal orbits are listed in Table 1. For example, in the table P-1 is short for Periapsis-1 which represents the first periapsis in the proximal orbits.

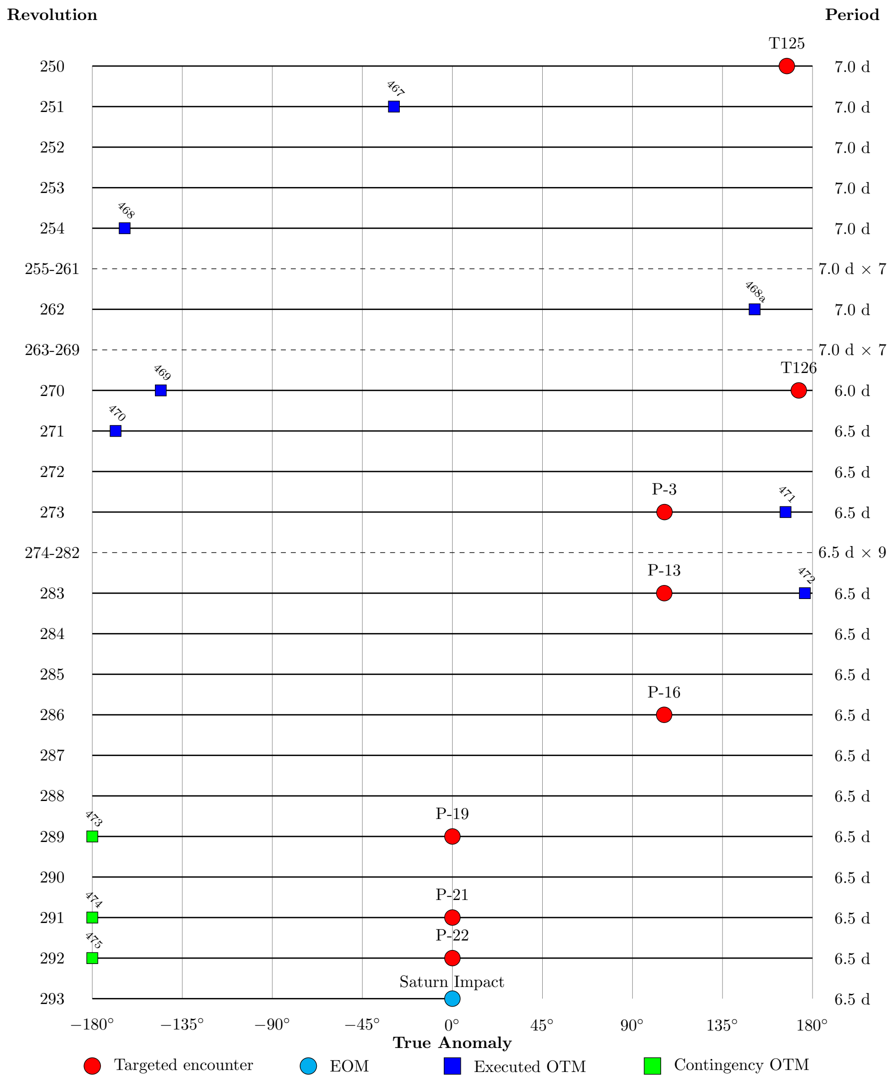


Figure 2: Titan-125 through Saturn Impact Orbital Events. Each solid line represents one revolution of Cassini around Saturn, with the horizontal position of the event indicating the true anomaly at which it occurred. The period of each revolution is noted along the right-hand side. Dashed lines signify a series of Saturn revolutions without an event.

Table 1: Proximal Orbit Periapsis Times from Reference Trajectory

Event	Periapsis Time (ET)	Event	Periapsis Time (ET)
P-1	26-Apr-2017 09:04:42.1888	P-12	06-Jul-2017 09:36:42.7486
P-2	02-May-2017 19:43:22.4098	P-13	12-Jul-2017 20:49:22.3219
P-3	09-May-2017 06:17:47.2715	P-14	19-Jul-2017 07:55:57.6614
P-4	15-May-2017 16:46:27.7053	P-15	25-Jul-2017 19:00:31.1418
P-5	22-May-2017 03:15:35.0821	P-16	01-Aug-2017 06:10:19.1564
P-6	28-May-2017 14:27:29.1099	P-17	07-Aug-2017 17:24:20.9870
P-7	04-Jun-2017 01:43:34.8965	P-18	14-Aug-2017 04:24:03.3366
P-8	10-Jun-2017 12:54:23.1067	P-19	20-Aug-2017 15:24:35.5666
P-9	16-Jun-2017 23:56:54.4513	P-20	27-Aug-2017 02:21:33.5029
P-10	23-Jun-2017 10:58:55.4278	P-21	02-Sep-2017 13:19:00.2190
P-11	29-Jun-2017 22:15:31.5965	P-22	09-Sep-2017 00:19:13.3122

The last two Titan encounters of the mission are described in Table 2. The reference trajectory flyby targets and the flyby differences are also given. The T126 target was intentionally altered to decrease the downstream ΔV cost and reduce deviations from the reference trajectory through the end of mission. This aimpoint change is noted in parentheses in the last three columns of Table 2.

Table 2: Targeted Encounter History (Titan-125 to Titan-126)

Encounter	Reference Trajectory Flyby Characteristics			150901 Reference Trajectory Target Conditions (Earth Mean Orbital Plane & Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
	V_∞ (km/s)	Period (days)	Inc. (deg)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	TCA (ET SCET)	Alt.[†] (km)	$\Delta\mathbf{B}\cdot\mathbf{R}$ (km)	$\Delta\mathbf{B}\cdot\mathbf{T}$ (km)	ΔTCA (sec)
Titan-125[‡]	5.4	7.3	63.8	−5865.94	−1414.75	29-Nov-2016 22:15:40	3158	−0.32	−0.13	−0.03
Titan-126[§, ¶]	5.4	6.5	62.2	−3719.84	992.12	22-Apr-2017 06:09:16	979	−0.62 *(−0.9)*	+0.71 *(+0.5)*	+0.02

[†] Flyby altitudes not explicitly targeted by maneuvers; reported altitudes from reference trajectory (relative to sphere).
[§] Target condition(s) changed via maneuver; the quantities in parentheses denote differences from reference trajectory.
[¶] Reported reconstructed flyby differences are based on preliminary OD estimates.

Information about the maneuvers performed to target T126, the last Titan flyby, during the F-ring orbit phase and to target specific periapsis times during the proximal orbits phase is shown in Table 3. The previous Titan flyby, T125, is also listed for reference. Design ΔV refers to the ΔV intended for the maneuver and reconstructed ΔV is the actual ΔV achieved as measured using tracking data after the maneuver is executed. Between T125 and the end of mission, seven maneuvers were performed (OTMs 467–472). There are also three contingency maneuvers for raising or lowering periapsis depending on the observed atmosphere at Saturn (OTMs 473–475). Each maneuver had a prime and backup opportunity. A backup maneuver would have been executed in the event of a problem linking or executing a prime maneuver. During this time period, OTM-467 was the only maneuver performed on main engine with the remaining maneuvers executed using the RCS thrusters. More details about the maneuvers are listed in the appendix in Tables 15 and 16.

Table 3: Maneuver History (OTMs 467–475)

Maneuver	Orbit Location	Maneuver Time (UTC SCET)	True Anomaly (deg)	Central Angle (deg)	Total Design $\Delta\mathbf{V}$[*] Mag. (m/s)	Total Design $\Delta\mathbf{V}$[*] RA (deg)	Total Design $\Delta\mathbf{V}$[*] Dec. (deg)	Total Reconstructed $\Delta\mathbf{V}$[*] Mag. (m/s)	Total Reconstructed $\Delta\mathbf{V}$[*] RA (deg)	Total Reconstructed $\Delta\mathbf{V}$[*] Dec. (deg)	Burn Type
Titan-125 (T125): 29-Nov-2016 22:15:40 ET, Altitude = 3158 km, Flyby ΔV = 551 m/s, 142.3 days to T126											
OTM-467	T125+5d	04-Dec-2016 11:58	−41.49	7049.37	0.994	163.86	−55.67	0.990	163.47	−55.75	MEA
OTM-468	∼apoapsis	24-Dec-2016 00:58	−163.81	6091.47	0.227	177.67	−14.88	0.225	177.95	−15.02	RCS
OTM-468a	∼periapsis	22-Feb-2017 15:49	151.06	2897.61	0.196	254.94	−10.16	0.199	255.02	−10.53	RCS
OTM-469[†, ‡]	T126−3d	18-Apr-2017 18:12	−145.74	314.93	0.060	195.12	−61.66	0.058	195.98	−61.68	RCS
Titan-126 (T126): 22-Apr-2017 06:09:16 ET, Altitude = 979 km, Flyby ΔV = 861 m/s, 146.2 days to Saturn impact											
OTM-470[‡]	Impact−143d	24-Apr-2017 17:52	−168.34	992.97	0.156	187.76	33.48	0.156	188.06	33.47	RCS
Periapsis-3 (P-3): 09-May-2017 06:17:47.2715 ET											
OTM-471[‡]	Impact−128d	10-May-2017 16:58	166.51	3535.23	0.020	210.05	14.08	0.021	210.16	13.94	RCS
Periapsis-13 (P-13): 12-Jul-2017 20:49:22.3219 ET											
OTM-472[‡]	Impact−62d	15-Jul-2017 12:21	176.16	1008.36	0.145	270.22	20.71	0.143	270.19	20.56	RCS
Periapsis-16 (P-16): 01-Aug-2017 06:10:19.1564 ET											
OTM-473	Impact−29d	17-Aug-2017 09:55	−180.00	179.55	………… *CONTINGENCY* …………						
Periapsis-19 (P-19): 20-Aug-2017 15:24:35.5666 ET											
OTM-474	Impact−16d	30-Aug-2017 09:01	−180.00	180.00	………… *CONTINGENCY* …………						
Periapsis-21 (P-21): 02-Sep-2017 13:19:00.2190 ET											
OTM-475	Impact−10d	05-Sep-2017 08:38	−180.00	180.00	………… *CONTINGENCY* …………						
Periapsis-22 (P-22): 09-Sep-2017 00:19:13.3122 ET											
Saturn Impact: 15-Sep-2017 12:08:00 ET (predicted)											

[*] Total $\Delta\mathbf{V}$ is the sum of $\Delta\mathbf{V}$s due to the burn, roll and yaw turns, the pointing-bias-fix turn for MEA burns, and the 5.8 mm/s deadband tightening for RCS burns. Expressed in Earth Mean Equator & Equinox of J2000.0 coordinates (EME2000). Mag. = magnitude, RA = right ascension, Dec. = declination.
[†] Target condition(s) changed via maneuver.
[‡] Reported reconstructed ΔV values are based on preliminary OD estimates.

MANEUVERS TARGETING FINAL TITAN ENCOUNTER (T126)

Four maneuvers were planned to target T126, the final satellite encounter in the mission: OTM-467 to cleanup flyby dispersions from the previous T125 flyby and target T126 in conjunction with downstream maneuvers, OTMs 468 and 468a designed in tandem to achieve the T126 aimpoint, and OTM-469 to fine-tune the T126 targeting. The T125 to T126 transfer involved 20 revolutions around Saturn over a five month period where Cassini would pass outside the edge of the F-ring prior to the final 'hop' over the main rings for the proximal orbits of the Grand Finale. The Cassini project decided that all remaining maneuvers (OTM-468 through OTM-472) were to be performed on RCS up to 0.5 m/s. Previously hydrazine was preserved by executing maneuvers with RCS only if the ΔV was under 0.25 m/s. With only a few maneuvers left to perform and bi-propellant running low, this restriction was lifted because hydrazine margins through end of mission were high.

OTM-467 (December 4, 2016)

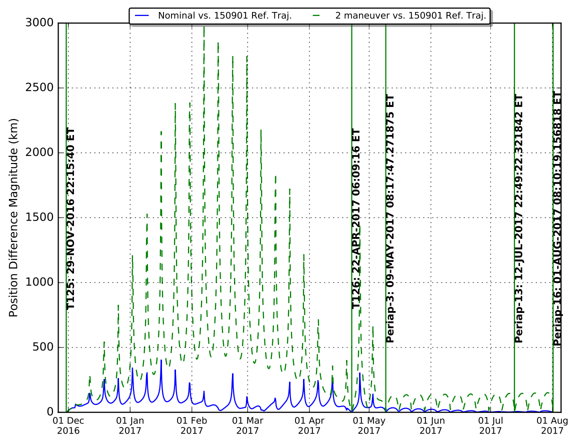
OTM-467 was performed on December 4, 2016 as a cleanup to the previous Titan flyby (T125) and to target the last Titan flyby (T126) on April 22, 2017. It was the last scheduled main engine burn in the mission with a ΔV size of about 0.99 m/s. OTM-467 was designed in an optimization chain with the next three deterministic maneuvers, OTMs 468, 468a and 470, to target the T126 flyby. OTM-469 was not included in the optimization chain since it was statistical and based on the performance of OTM-468a. Nominally flyby cleanup maneuvers during the mission were designed with the next maneuver in an optimization chain. At only one other time was a cleanup maneuver designed in conjunction with two subsequent maneuvers: OTM-164 chained with OTMs 164a and 165 to target Enceladus-5 (E5) on October 9, 2008 (see Reference 9).

Table 4: OTM-467 Strategy ΔV Comparisons

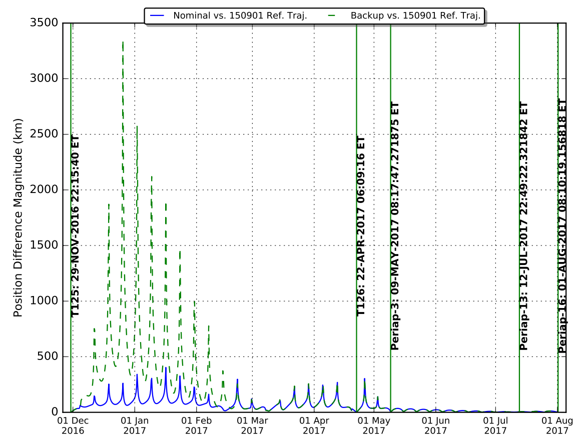
Target	Maneuver	Nominal: Prime (3-Mvr. Strat.)	Case 1: Prime (2-Mvr. Strat.)		Case 2: Backup (3-Mvr. Strat.)	
		ΔV (m/s)	ΔV (m/s)	Diff. (m/s)	ΔV (m/s)	Diff. (m/s)
	OTM-467	0.994	1.022	0.028	2.944	1.950
	OTM-468	0.206	0.120	−0.086	0.618	0.412
T126	OTM-468a	0.241	—	−0.241	0.062	−0.179
P-3	OTM-470	0.219	0.773	0.554	0.219	0.000
P-13	OTM-471	0.071	0.254	0.183	0.071	0.000
P-16	OTM-472	0.014	0.010	−0.004	0.014	0.000
	Total ΔV	1.745	2.178	0.434	3.927	2.182

Table 4 presents the ΔV comparisons between the explored maneuver strategies for OTM-467. The total projected cost for OTMs 467 through 472 was about 1.75 m/s at the prime maneuver opportunity for OTM-467 and the three-maneuver optimization chain strategy. In each maneuver strategy case OTM-467 does the majority of the B-plane change to accomplish the T126 targeting requirements. The post-T126 maneuvers (OTMs 470–472) were also predicted to decrease in ΔV size at each opportunity. Designing OTM-467 with the next two maneuvers also would keep the deviations below 500 km, as shown in Figure 3a. Implementing the two-maneuver strategy for OTM-467 (chaining OTMs 467 and 468 to target T126) was predicted to cost 0.434 m/s over the adopted three-maneuver strategy. The two-maneuver strategy also yielded higher trajectory deviations from the reference trajectory, with deviations reaching 3000 km through the T126 flyby.

Finally, the backup opportunity for OTM-467 was scheduled less than 24 hours after the prime at a true anomaly 124° on the other side of periapsis. Like the prime maneuver, it would be designed in conjunction with OTMs 468 and 468a. The backup maneuver would be nearly three times larger than the prime maneuver at 2.92 m/s and add an overall cost of 2.2 m/s over the prime. Additionally, the trajectory deviations following the backup maneuver would be greater than the prime through the T126 flyby. As a precautionary measure, the prime maneuver was uplinked early to mitigate the chance of falling to the costlier backup opportunity. The backup maneuver was also unfavorable since OTM-468 would need to be performed on main engine (0.6 m/s) and would require contingency work during the holidays.



(a) Prime: Three Maneuvers vs. Two Maneuvers



(b) Prime vs. Backup

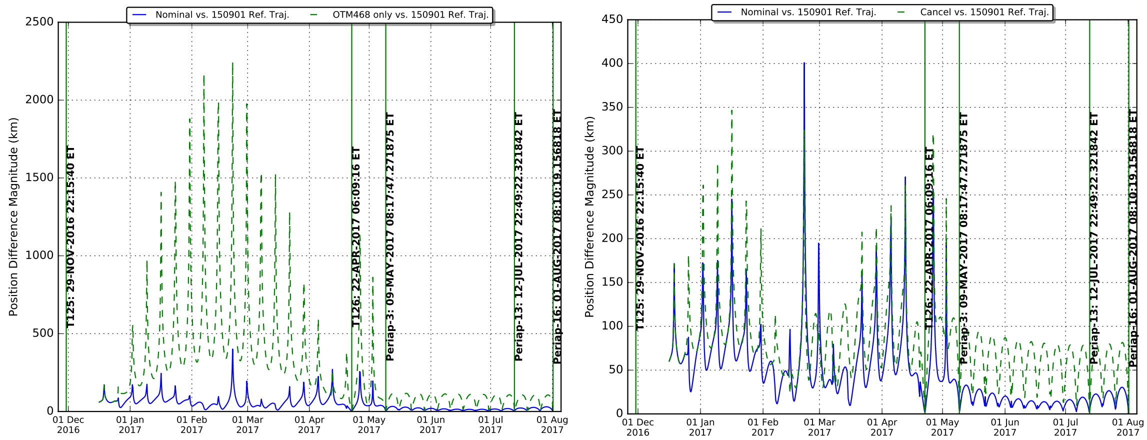
Figure 3: OTM-467 Deviations from Reference Trajectory

OTM-468 (December 24, 2016)

OTM-468 was performed on December 24, 2016 to target the T126 flyby on April 22, 2017. It was designed in an optimization chain with the next maneuver OTM-468a. Table 5 presents the ΔV comparisons between the strategies that were considered for OTM-468. As can be seen in the table, OTM-468 chained with OTM-468a saves 0.4 m/s over targeting T126 via OTM-468 only (Case 2) or OTM-468a only (Case 3). Performing only OTM-468 causes the trajectory deviations to grow over 2000 km prior to T126 and brings OTM-470 to a main engine size of 0.77 m/s. Although skipping OTM-468 and targeting OTM-468a to T126 does not greatly affect the trajectory deviations leading to T126 (see Figure 4b), OTM-468a becomes a large RCS maneuver of 0.46 m/s. The backup maneuver cost was deemed negligible at 64 mm/s.

Table 5: OTM-468 Strategy ΔV Comparisons

Target	Maneuver	Nominal: OTM-468 Chain ΔV (m/s)	Case 1: Backup ΔV (m/s)	Case 1: Backup Diff. (m/s)	Case 2: OTM-468 Only ΔV (m/s)	Case 2: OTM-468 Only Diff. (m/s)	Case 3: OTM-468a Only ΔV (m/s)	Case 3: OTM-468a Only Diff. (m/s)
T126	OTM-468	0.227	0.183	−0.044	0.154	−0.073	—	−0.227
	OTM-468a	0.201	0.296	0.095	—	−0.201	0.457	0.255
P-3	OTM-470	0.228	0.239	0.011	0.763	0.535	0.581	0.353
P-13	OTM-471	0.080	0.082	0.002	0.249	0.170	0.101	0.021
P-16	OTM-472	0.017	0.017	0.000	0.007	−0.010	0.024	0.007
	Total ΔV	0.753	0.817	0.064	1.173	0.420	1.163	0.410



(a) OTM-468 Chain vs. OTM-468 Only (Case 2)

(b) OTM-468 Chain vs. OTM-468a Only (Case 3)

Figure 4: OTM-468 Deviations from Reference Trajectory

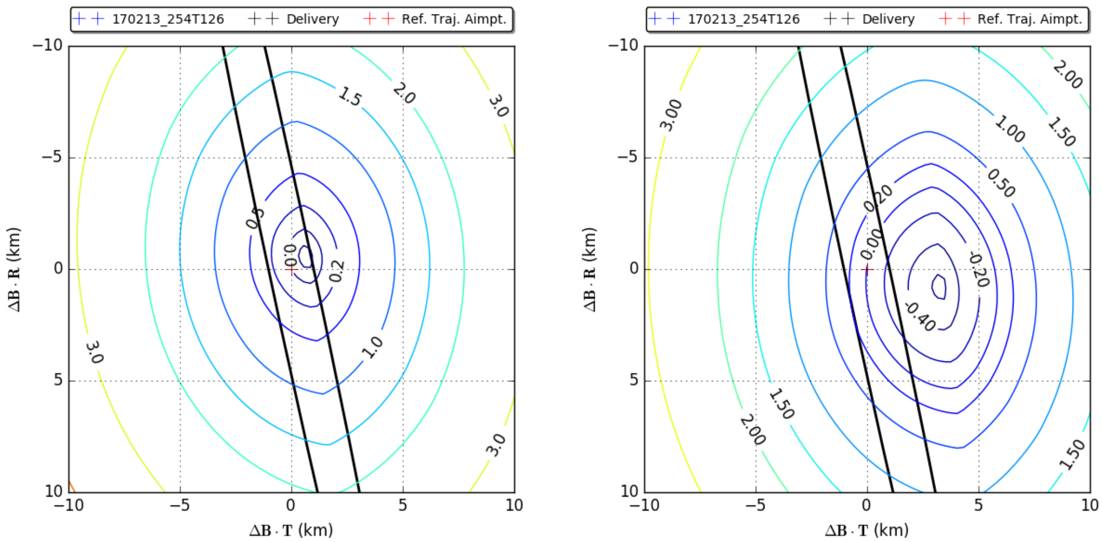
OTM-468a (February 22, 2017)

OTM-468a was at first a statistical maneuver that was added after the Solstice Mission began in order to reduce the size of OTM-469, the final approach maneuver to T126. This in turn would avoid the larger flyby errors that can be caused by a main engine burn at approach (see "Navigation Performance" section). In the Solstice Navigation Plan, OTMs 467, 468, and 469 were the only maneuvers originally intended to target T126 (see Reference 17). Without OTM-468a, the predicted mean value for OTM-469 was 147 mm/s with a ΔV90 of 273 mm/s. By adding OTM-468a, the predicted mean value for OTM-469 was reduced to 79 mm/s and the ΔV90 to 168 mm/s, thus better ensuring OTM-469 would remain an RCS-size maneuver (i.e., below 0.5 m/s). The prime and backup locations for OTM-468a were selected to keep ΔV costs low. They were also placed to avoid four locations where the gradients of the targeting components $\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and time-of-flight become co-planar.

Table 6: OTM-468a Strategy ΔV Comparisons

Target	Maneuver	Nominal: Prime	Case 1: Backup (Ref. Tgt.)		Case 2: Backup (New Tgt.)	
		ΔV (m/s)	ΔV (m/s)	Diff. (m/s)	ΔV (m/s)	Diff. (m/s)
T126	OTM-468a	0.1962	0.4643	0.2681	0.4545	0.2583
P-3	OTM-470	0.2317	0.9083	0.6767	0.0281	−0.2036
P-13	OTM-471	0.0603	0.2464	0.1861	0.0187	−0.0416
P-16	OTM-472	0.0072	0.0074	0.0002	0.0058	−0.0014
	Total ΔV	0.4954	1.6264	1.1310	0.5072	0.0118

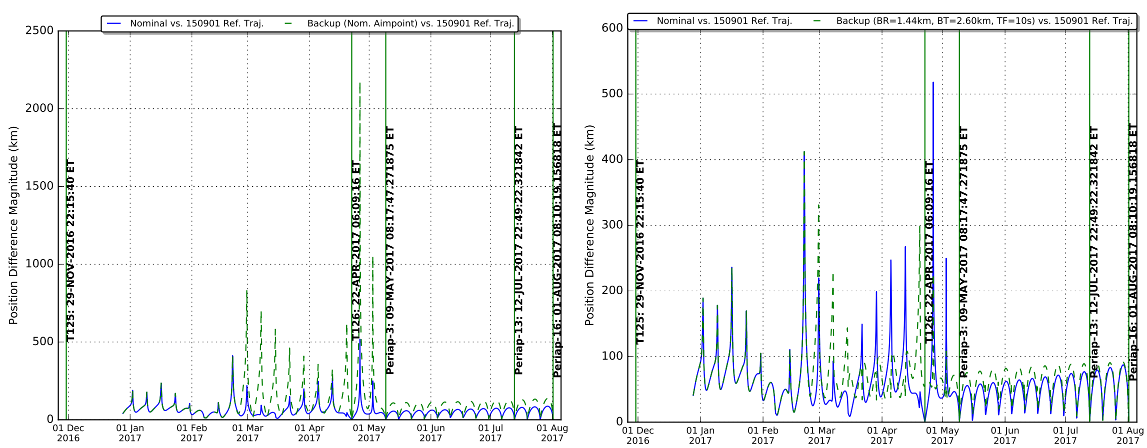
As seen with Case 1 in Table 6, the backup maneuver targeted to the reference trajectory T126 aimpoint added a 1.13 m/s cost with a large OTM-468a backup ΔV of 0.46 m/s and a large main engine sized OTM-470 of nearly 1 m/s. By changing the T126 aimpoint ($\mathbf{B}\cdot\mathbf{R}$ by $+1.44$ km, $\mathbf{B}\cdot\mathbf{T}$ by $+2.60$ km) and the time-of-flight by 10 sec, the backup maneuver cost over the prime reduces to a negligible 12 mm/s (see Case 2 in Table 6). With the T126 target change, the backup maneuver remains 0.45 m/s, but OTMs 470 and 471 become small RCS-size maneuvers and the downstream trajectory deviations are reduced (see Figure 6b). The B-plane change alone accounts for only about 0.5 m/s of the ΔV savings, as shown in the contour plot in Figure 5b, with the 10 sec time-of-flight change making up the rest of the 1.13 m/s cost. As seen in Figure 5a, a similar target change for the prime maneuver would yield a very small ΔV savings. OTM-468a marked the first time different B-plane targets were implemented for the prime and backup designs for a Cassini maneuver. At the time of the OTM-468a design, the cost to skip OTM-468a and perform the T126 correction at OTM-469 grew to nearly 11 m/s, with OTM-469 becoming 3.4 m/s. Although the backup maneuver was nearly 0.5 m/s, if performed it would be executed via the RCS thrusters to avoid a partial main engine burn due to the depletion of bi-propellant. Hence an early uplink of OTM-468a was prioritized. Note, the T126 aimpoint change for the backup maneuver was not needed as the prime maneuver was successfully performed.



(a) OTM-468a Prime ΔV Cost Contours

(b) OTM-468a Backup ΔV Cost Contours

Figure 5: OTM-468a ΔV Cost Contours



(a) Prime vs. Backup

(b) Prime vs. Alternate Backup

Figure 6: OTM-468a Deviations from Reference Trajectory

OTM-469 (April 18, 2017)

OTM-469 was the final approach maneuver targeted to the T126 flyby on April 22, 2017. To save downstream ΔV, the T126 aimpoint was changed from the reference trajectory values by -0.9 km in $\mathbf{B}\cdot\mathbf{R}$ and $+0.5$ km in $\mathbf{B}\cdot\mathbf{T}$ for both the prime and backup maneuver designs. OTM-469 itself remained about 0.6 m/s in size, but 167 mm/s was projected to be saved by implementing the target change (see Case 2 in Table 7) and OTM-470 reduced in magnitude. This savings can be seen in the ΔV cost at T126 B-plane contour plot in Figure 7. The aimpoint change also mitigated the trajectory deviations significantly following T126 as shown in Figure 8b. The backup maneuver designed with the new aimpoint for T126 yielded a negligible cost of 16 mm/s over the prime maneuver. Not performing OTM-469 would cost 2.5 m/s, where most of the cost comes from the increased size of OTM-470 (see Case 3 in Table 7). OTM-469 cancellation would also result in the trajectory deviations going beyond 500 km soon after T126 (see Figure 8a).

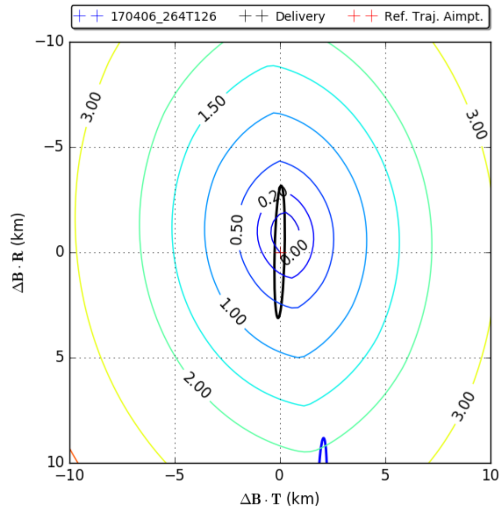
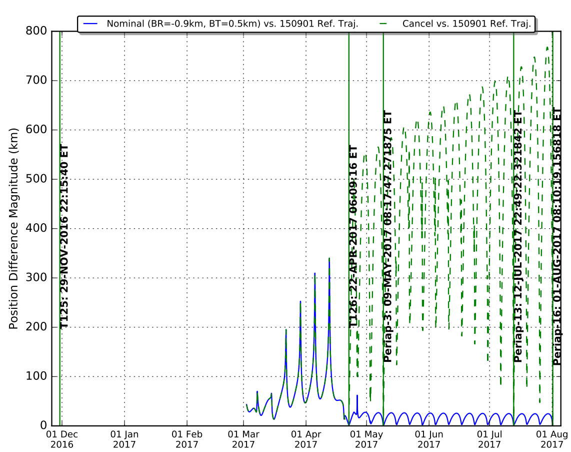


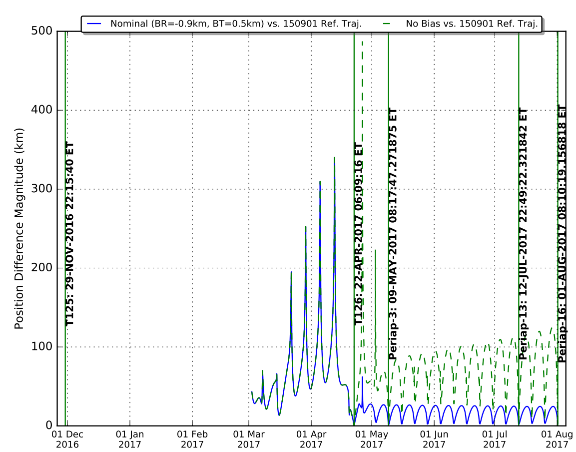
Figure 7: OTM-469 ΔV Cost Contours

Table 7: OTM-469 Strategy ΔV Comparisons

Target	Maneuver	Nominal: Prime (New Tgt.) ΔV (m/s)	Case 1: Backup (New Tgt.) ΔV (m/s)	Case 1: Diff. (m/s)	Case 2: Prime (Ref. Tgt.) ΔV (m/s)	Case 2: Diff. (m/s)	Case 3: Cancel OTM-469 ΔV (m/s)	Case 3: Diff. (m/s)
T126	OTM-469	0.0595	0.0911	0.0316	0.0587	-0.0009	—	-0.0595
P-3	OTM-470	0.1396	0.1316	-0.0080	0.2476	0.1080	2.4458	2.3062
P-13	OTM-471	0.0096	0.0034	-0.0063	0.0526	0.0430	0.0868	0.0771
P-16	OTM-472	0.0022	0.0008	-0.0015	0.0192	0.0170	0.1593	0.1571
	Total ΔV	0.2111	0.2268	0.0157	0.3782	0.1671	2.6919	2.4808



(a) Prime vs. Cancel

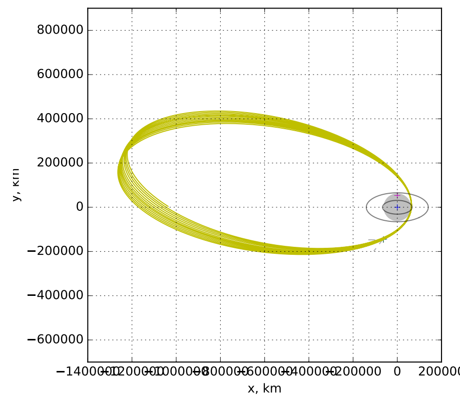


(b) Prime vs. Prime No Bias

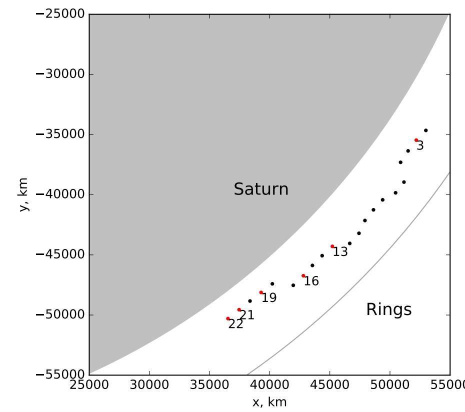
Figure 8: OTM-469 Deviations from Reference Trajectory

PROXIMAL ORBIT MANEUVERS (GRAND FINALE)

Following the T126 flyby, Cassini was placed in a 6.5 day orbit around Saturn that would pass 22 times through the gap between the inner D-ring and the Saturn atmosphere. To enable high-quality science observations sensitive to trajectory dispersions, three maneuvers were planned by Cassini Navigation to control the timing of the ring plane crossings and periapses: OTMs 470, 471, and 472. Initially, all trajectory deviations at 22 periapses were required to be controlled and maintained under 250 km. Under further study, the Cassini Project project decided that only the trajectory deviations at P-3, P-14, and P-16 were required to be under 250 km. The Cassini Navigation Team developed a three-maneuver control strategy to target P-3, P-13, and P-16 (P-13 was targeted instead of P-14 to lower the ΔV cost).[18,19] OTMs 470, 471, and 472 were targeted to two hours after P-3, P-13, and P-16, respectively, at the Cartesian states defined in the reference trajectory to within a $2 \times 2 \times 2$ km tolerance. Figure 9 shows Cassini's trajectory during the proximal orbits phase with the implemented maneuver plan.



(a) View of the trajectory along the orbit normal direction. *Spacecraft motion is in the clockwise direction.*



(b) Ring Plane Crossings at Periapsis. *P-2 through P-22 are represented by dots ordered right to left with targeted periapses numbered and indicated by red dots.*

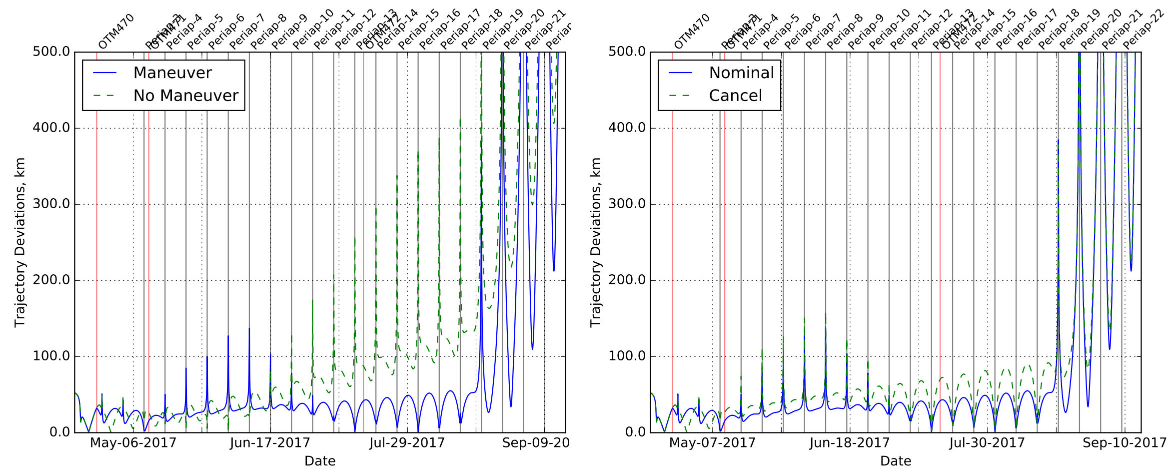
Figure 9: Cassini Trajectory During Proximal Orbits

OTM-470 (April 24, 2017)

OTM-470 was performed two days after the T126 flyby to target the third periapsis state as defined in the reference trajectory (two hours after P-3). Because of the small Titan flyby miss of 300 m, OTM-470 remained a small RCS burn with a magnitude of 0.156 m/s. Performing OTM-470 at either the prime or backup opportunity, or cancelling the maneuver, yielded similar downstream ΔV costs (see Table 8). Additionally, trajectory deviations were predicted to remain below 250 km through P-18 with or without OTM-470 as seen in Figure 10 and Table 9. However, OTM-471 would still be required regardless if OTM-470 was executed or not. Also, performing OTM-470 would mitigate the growth of OTM-471 (see Case 2 in Table 8). Note, the values shown in Table 9 are the predicted trajectory deviations based on the available information at the time.

Table 8: OTM-470 Strategy ΔV Comparisons

Target	Maneuver	Nominal: Prime ΔV (m/s)	Case 1: Backup ΔV (m/s)	Case 1: Backup Diff. (m/s)	Case 2: Cancel ΔV (m/s)	Case 2: Cancel Diff. (m/s)
P-3	OTM-470	0.156	0.182	0.026	—	−0.156
P-13	OTM-471	0.043	0.042	−0.001	0.216	0.172
P-16	OTM-472	0.021	0.019	−0.002	0.020	0.000
	Total ΔV	0.220	0.243	0.023	0.236	0.016



(a) Prime vs. No Maneuvers

(b) Prime vs. Cancel OTM-470

Figure 10: OTM-470 Deviations from Reference Trajectory

Table 9: OTM-470 Deviations From Reference Trajectory at Periapses. *P-3, P-13, and P-16 are targeted periapses (highlighted). Deviations above 250 km are indicated in bold (P-3, P-14 and P-16 deviations required to be under 250 km).*

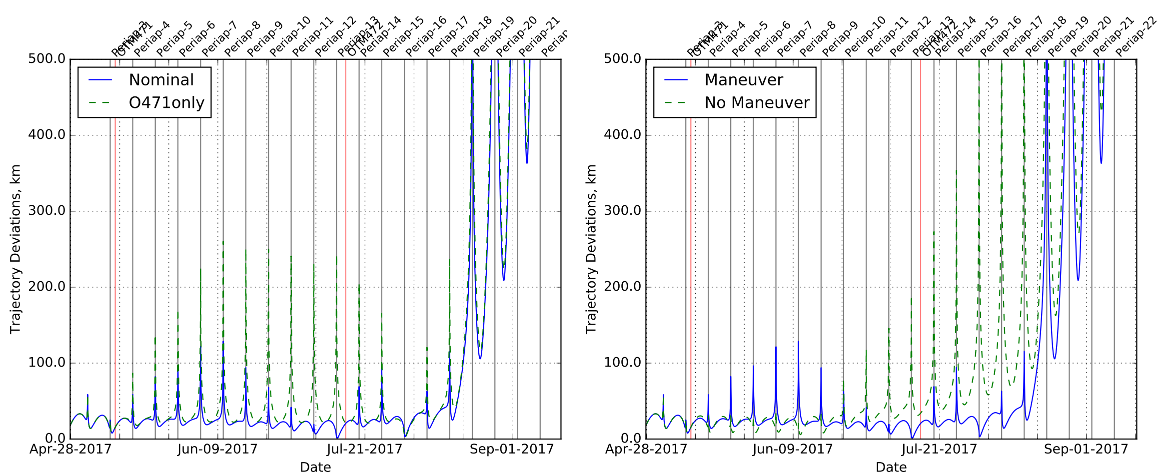
Event	Date	Case 1: OTM-470 Prime (km)	Case 2: OTM-470 Backup (km)	Case 3: OTM-471 Only (km)	Case 4: No Future OTMs (km)
P-3	09-May-2017	3.342	3.536	15.53	15.53
P-4	15-May-2017	52.37	50.08	77.30	11.75
P-5	22-May-2017	86.54	82.37	113.5	4.404
P-6	28-May-2017	106.7	102.6	134.1	2.058
P-7	04-Jun-2017	133.0	129.2	157.8	1.092
P-8	00-Jun-2017	138.4	134.9	160.3	22.99
P-9	16-Jun-2017	103.8	100.5	124.7	82.21
P-10	23-Jun-2017	78.23	75.23	97.83	132.1
P-11	29-Jun-2017	50.03	47.96	65.96	177.9
P-12	06-Jul-2017	23.43	22.35	35.19	222.9
P-13	12-Jul-2017	1.323	1.300	6.805	**264.8**
P-14	19-Jul-2017	16.36	13.55	17.17	**300.7**
P-15	25-Jul-2017	8.813	7.086	12.68	**337.9**
P-16	01-Aug-2017	1.321	1.417	5.678	**374.6**
P-17	07-Aug-2017	10.79	9.659	6.292	**411.0**
P-18	14-Aug-2017	28.54	25.53	21.22	**441.0**
P-19	20-Aug-2017	**413.5**	**407.9**	**407.3**	**828.8**
P-20	27-Aug-2017	**1302**	**1292**	**1305**	**1711**
P-21	02-Sep-2017	**2766**	**2750**	**2787**	**3150**
P-22	09-Sep-2017	**4772**	**4749**	**4820**	**5120**

OTM-471 (May 10, 2017)

Although OTM-471 was targeted to the thirteenth periapsis state from the reference trajectory (two hours after P-13), keeping the trajectory deviation at P-14 below 250 km was prioritized for science. The prime and backup OTM-471 designs were both around 20 mm/s and remained stable through each maneuver design iteration. Unlike most backup maneuvers that are scheduled one day after the prime, OTM-471 backup was scheduled four days later. Like OTM-470 backup, OTM-471 backup did not incur a ΔV penalty and trajectory deviations were similar to the prime maneuver (see Case 1 in Table 10). Performing OTM-471 only targeted to P-16 and skipping OTM-472 would potentially save 53 mm/s but trajectory deviations at Periapsis-13 would grow and nearly reach the 250 km limit (see Case 2 in Table 10 and Figure 11a). Canceling OTM-471 would result in OTM-472 increasing to 107 mm/s, but the cost would only be 31 mm/s and the 250 km trajectory deviation requirement for both P-13 and P-14 would still be met. The same argument to perform OTM-470 was applied to OTM-471: performing OTM-471 would keep OTM-472 from growing. Table 11 presents the predicted trajectory deviations based on the available information at the time of the OTM-471 design.

Table 10: OTM-471 Strategy ΔV Comparisons

Target	Maneuver	Nominal: Prime	Case 1: Backup		Case 2: OTM-471 Only		Case 3: Cancel OTM-471	
		ΔV (m/s)	ΔV (m/s)	Diff. (m/s)	ΔV (m/s)	Diff. (m/s)	ΔV (m/s)	Diff. (m/s)
P-13	OTM-471	0.020	0.020	0.000	0.023	0.003	—	−0.020
P-16	OTM-472	0.056	0.052	−0.004	—	−0.056	0.107	0.051
	Total ΔV	0.076	0.072	−0.004	0.023	−0.053	0.107	0.031



(a) Prime vs. OTM-471 Only

(b) Prime vs. Cancellation

Figure 11: OTM-471 Deviations from Reference Trajectory

Table 11: OTM-471 Deviations From Reference Trajectory at Periapses. *P-3, P-13, and P-16 are targeted periapses (highlighted). Deviations above 250 km are indicated in bold (P-3, P-14 and P-16 deviations required to be under 250 km).*

Event	Date	Case 1: OTM-471 Prime (km)	Case 2: OTM-471 Backup (km)	Case 3: OTM-471 Only (km)	Case 4: OTM-472 Only (km)	Case 5: No Future OTMs (km)
P-3	09-May-2017	26.16	26.16	26.16	26.16	26.16
P-4	15-May-2017	60.55	28.50	89.36	31.86	31.86
P-5	22-May-2017	84.28	52.19	141.5	32.31	32.31
P-6	28-May-2017	103.4	75.35	185.0	32.87	32.87
P-7	04-Jun-2017	126.9	102.5	233.7	37.04	37.04
P-8	10-Jun-2017	129.8	109.0	**262.2**	20.39	20.39
P-9	16-Jun-2017	94.28	77.28	**251.7**	34.14	34.14
P-10	23-Jun-2017	68.00	54.84	**250.2**	79.11	79.11
P-11	29-Jun-2017	43.21	34.58	247.0	119.5	119.5
P-12	06-Jul-2017	19.98	15.90	245.8	158.7	158.7
P-13	12-Jul-2017	1.769	1.812	248.2	195.4	195.4
P-14	19-Jul-2017	68.86	62.86	206.5	26.01	**275.6**
P-15	25-Jul-2017	94.18	90.94	165.4	46.27	**354.3**
P-16	01-Aug-2017	7.76	8.16	3.354	9.095	**557.8**
P-17	07-Aug-2017	63.89	61.22	126.2	18.39	**716.7**
P-18	14-Aug-2017	119.3	113.2	248.9	24.94	**874.8**
P-19	20-Aug-2017	**1107**	**1096**	**1310**	**960**	**1955**
P-20	27-Aug-2017	**2743**	**2726**	**3031**	**2537**	**3693**
P-21	02-Sep-2017	**5348**	**5323**	**5730**	**5077**	**6394**
P-22	09-Sep-2017	**9062**	**9026**	**9548**	**8719**	**10210**

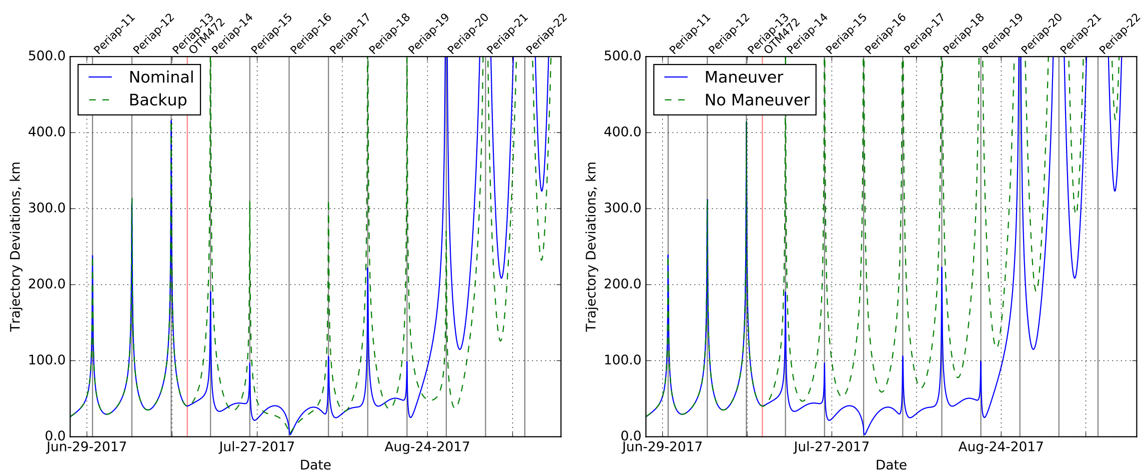
OTM-472 (July 15, 2017)

OTM-472 was the final maneuver used to control the trajectory deviations in the proximal orbits phase, targeting to two hours after P-16. Without OTM-472, all periapses beginning with P-14 would be well above the 250 km deviation requirement (see Case 3 in Table 12), necessitating the execution of either OTM-472 prime or backup. By targeting the prime maneuver to P-16, all trajectory deviations at periapses between P-14 and P-19 remain below 250 km from the reference trajectory (see Case 1 in Table 12). The P-14 timing offset with the prime maneuver remains small, but grows to about 10 seconds without it (see Figure 13). Targeting the backup to P-16, however, does not control the deviations well prior to and after P-16. In fact, Periapses 14, 15, 17, and 18 are all well above the 250 km deviation limit (see Case 2 in Table 12 and Figure 12a), most notably P-14 at 621.1 km. Without a viable targeting option for the backup maneuver, it became imperative to rely on the prime maneuver which was successfully uplinked early at the first of three opportunities.

Table 13 shows the design iterations for OTM-472 prime and backup. The design of OTM-472 presented its own set of challenges. As can be seen in Table 7, at the time of the OTM-469 design, OTM-470 was the larger of the three proximal maneuvers and OTM-472 was negligible. The small force* ΔVs after OTM-472 in July 2017 were not made available for the Cassini OD team in time

*The small propulsive ΔVs, on the order of a few millimeters per second, imparted on the spacecraft from unbalanced RCS thrusting for science activities and angular momentum management of the reaction wheels.

for the OTM-470 design, so OTM-472 still looked to be negligible. However, OTM-472 became larger than OTM-471 by the time OTM-471 was designed (refer to Table 10). After P-3 on May 9, 2017, it was observed that the size of OTM-472 continued to grow (see Table 13) as well as the trajectory deviations. Estimates of the small forces ΔV predictions around the time of OTM-472 were not provided until May 16, 2017 to the Cassini Orbit Determination (OD) Team, so previous maneuver designs were based on an incomplete set of small forces. Additionally, the OD team began observing a "drag-like" effect at periapsis which caused the periapsis times to consistently decrease to an earlier time at each periapsis passage. This effect disappeared after P-11 on June 29, 2017 and is reflected in the stable OTM-472 designs of about 0.14 to 0.15 m/s for the last two weeks (see last five rows of Table 13).



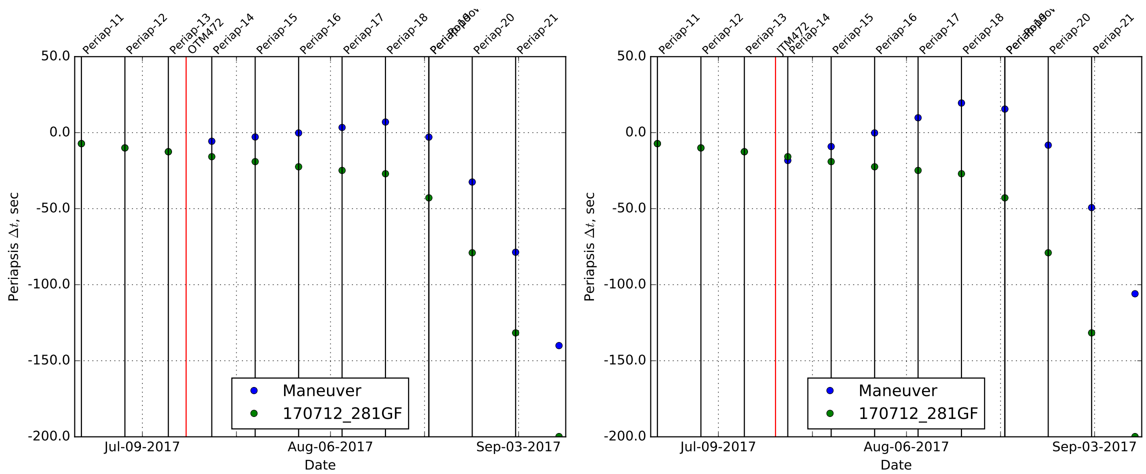
(a) Prime vs. Backup

(b) Prime vs. Cancellation

Figure 12: OTM-472 Deviations from Reference Trajectory

Table 12: OTM-472 Deviations From Reference Trajectory at Periapses. *P-13 and P-16 are targeted periapses (highlighted). Deviations above 250 km are indicated in bold (P-14 and P-16 deviations required to be under 250 km).*

Event	Date	Case 1: OTM-472 Prime (km)	Case 2: OTM-472 Backup (km)	Case 3: No Future OTMs (km)
P-13	12-Jul-2017	**425.8**	**425.8**	**425.8**
P-14	19-Jul-2017	192.6	**621.1**	**537.5**
P-15	25-Jul-2017	97.17	**310.0**	**647.7**
P-16	01-Aug-2017	8.58	5.665	**762.5**
P-17	07-Aug-2017	115.2	**333.0**	**843.7**
P-18	14-Aug-2017	239.2	**669.7**	**927.4**
P-19	20-Aug-2017	101.9	**533.4**	**1472**
P-20	27-Aug-2017	1116	**282.1**	**2713**
P-21	02-Sep-2017	**2701**	**1692**	**4521**
P-22	09-Sep-2017	**4807**	**3636**	**6857**



(a) Prime vs. Cancellation

(b) Backup vs. Cancellation

Figure 13: OTM-472 Periapsis Timings

Table 13: OTM-472 Prime and Backup Design History

Prime MAPDF* ID	OD Solution†	ΔV Mag. (m/s)	ΔV RA (deg)	ΔV Dec. (deg)	Backup MAPDF* ID	OD Solution†	ΔV Mag. (m/s)	ΔV RA (deg)	ΔV Dec. (deg)
O472_x	170510_271GF	0.0463	268.3810	36.8215	J472_x	170510_271GF	0.0460	100.1384	4.4069
O472_x	170515_271GF	0.0393	272.0077	47.6309	J472_x	170515_271GF	0.0387	97.6864	15.8594
O472_x	170516_271GF	0.0593	269.9283	34.8913	J472_x	170516_271GF	0.0588	98.8314	2.3508
O472_x	170518_271GF	0.0473	270.1443	41.9994	J472_x	170518_271GF	0.0468	98.8169	9.4954
O472_x	170522_271GF	0.0578	270.9608	36.3675	J472_x	170522_271GF	0.0572	98.0121	3.7673
O472_x	170525_271GF	0.0610	270.8254	35.0555	J472_x	170525_271GF	0.0604	98.0851	2.4560
O472_x	170530_271GF	0.0915	270.3972	26.3174	J472_x	170530_271GF	0.0910	98.2228	-6.2676
O472_x	170601_276GF	0.0899	270.3396	26.9552	J472_x	170601_276GF	0.0894	98.2916	-5.6251
O472_x	170604_276GF	0.0949	270.3593	26.2860	J472_x	170604_276GF	0.0944	98.2570	-6.2949
O472_x	170608_276GF	0.1000	270.4462	25.3874	J472_x	170608_276GF	0.0994	98.1540	-7.1993
O472_x	170611_276GF	0.1157	270.2786	23.4379	J472_x	170611_276GF	0.1151	98.2623	-9.1284
O472_x	170616_1_276GF	0.1153	270.2239	23.5126	J472_x	170616_1_276GF	0.1147	98.3159	-9.0491
O472_x	170619_276GF	0.1319	270.2894	21.8262	J472_x	170619_276GF	0.1312	98.2128	-10.7347
O472_x	170622_276GF	0.1320	270.2644	21.7542	J472_x	170622_276GF	0.1313	98.2351	-10.8041
O472_x	170626_276GF	0.1524	270.2788	20.2444	J472_x	170626_276GF	0.1516	98.1845	-12.3078
O472_d	170630_281GF	0.1504	270.1741	20.2543	J472_x	170630_281GF	0.1497	98.2870	-12.2884
O472_d	170705_281GF	0.1494	270.3035	20.3328	J472_x	170705_281GF	0.1487	98.1625	-12.2224
O472_d	170706_281GF	0.1435	270.3657	20.8178	J472_x	170706_281GF	0.1428	98.1141	-11.7455
O472_d	170710_281GF	0.1448	270.3703	20.6214	J472_x	170710_281GF	0.1441	98.1045	-11.9414
O472_d	170712_281GF	0.1447	270.2176	20.7136	J472_x	170712_281GF	0.1440	98.2555	-11.8355

* Maneuver Performance Data File (MAPDF) ID: 'O' for prime and 'J' for backup, OTM number (3 digits), OTM letter or '_' if no letter, and version letter

† OD solution naming convention: data cutoff date, Saturn revolution number, and target name (GF, Grand Finale)

POP-UP AND POP-DOWN CONTINGENCY MANEUVERS

For Cassini's last five revolutions around Saturn in the Grand Finale, there is a large 5+ minutes timing uncertainty to the atmospheric entry since Saturn's atmosphere is not well determined and the spacecraft begins dipping into it. The atmosphere will be assessed by Cassini mission planners at each ring plane crossing using thruster duty cycle data to determine if a "pop-up" to raise periapsis or "pop-down" to lower periapsis will be needed, the latter of which is desired for better measurements of the atmosphere. Since each ring plane crossing is separated by only seven days and the periapsis altitude to achieve will depend on the anticipated atmosphere at each of these crossings, the targets of each of the contingency maneuvers will not be known until just a couple of days before their executions. One or more of the following three maneuvers may be performed in the weeks prior to Cassini's plunge into Saturn on September 15, 2017: OTM-473, a "pop-up" maneuver (for spacecraft health and safety reasons) scheduled for August 17, 2017 and targeted to P-19; OTM-474, a "pop-down" maneuver planned for August 30, 2017 and targeted to P-21, and OTM-475, a "pop-down" maneuver scheduled for September 5, 2017 and targeted to P-22.

NAVIGATION PERFORMANCE

The "navigation cost" for each encounter indicates the difference between the deterministic ΔV from the reference trajectory and the ΔV actually spent during the encounter span. For the final T125 to T126 transfer, the navigation cost was 0.362 m/s (reference trajectory determistic ΔV 1.113 m/s; predicted mean ΔV 1.325 m/s, standard deviation 0.368 m/s, and ΔV90 1.8 m/s; actual ΔV total 1.476 m/s). In Table 14, the average navigation cost per flyby for the Prime, Equinox, and Solstice Missions are given. For the entire Solstice Mission, the average navigation cost per flyby was 0.135 m/s, well under the target of 0.3 m/s per flyby set for the mission. A plot of the accumulated navigation cost for the entire mission is shown in Figure 14.

Table 14: Average Navigation ΔV Cost per Encounter For Entire Mission

Mission	Flyby Span	Number of Flybys	Navigation ΔV Cost Mean (m/s)	Navigation ΔV Cost Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta – E4	54	0.325	0.594
Equinox (9/2008 – 9/2010)	E5 – T72	36	0.447	0.978
Solstice (9/2010 – 4/2017)	T73 – T126	70	0.135	0.146

There were only two exceptions to this tremendous maneuver performance during the Saturn tour: OTM-145 and OTM-169. As indicated in Figure 14, OTM-145 was a main engine burn near the end of the Prime Mission. It was the final approach maneuver targeted to a low 1000 km Titan-41 (T41) flyby. The use of the main engine for the final approach maneuver proved costly; the larger execution errors associated with a 0.3 m/s main engine burn translated into a nearly 5 km miss at T41 which then manifested into a large 3 m/s downstream penalty. As a result, the Cassini Project decided that all future approach maneuvers would be performed only on RCS. OTM-169, the approach maneuver targeting Titan-46 (T46), was an RCS maneuver performed near the beginning of the Equinox Mission as shown in Figure 14. With a large ΔV of 0.23 m/s, it significantly underperformed yielding a nearly 10 km miss at T46 (a low 1100 km Titan flyby) and a downstream cost of over 7 m/s. This sub-par performance was due to the degradation of the primary RCS A-branch thrusters, leading to a swap to the redundant B-branch thrusters in March 2009.[9] This large Titan miss could have been mitigated if an auxiliary maneuver such as OTM-168a had been

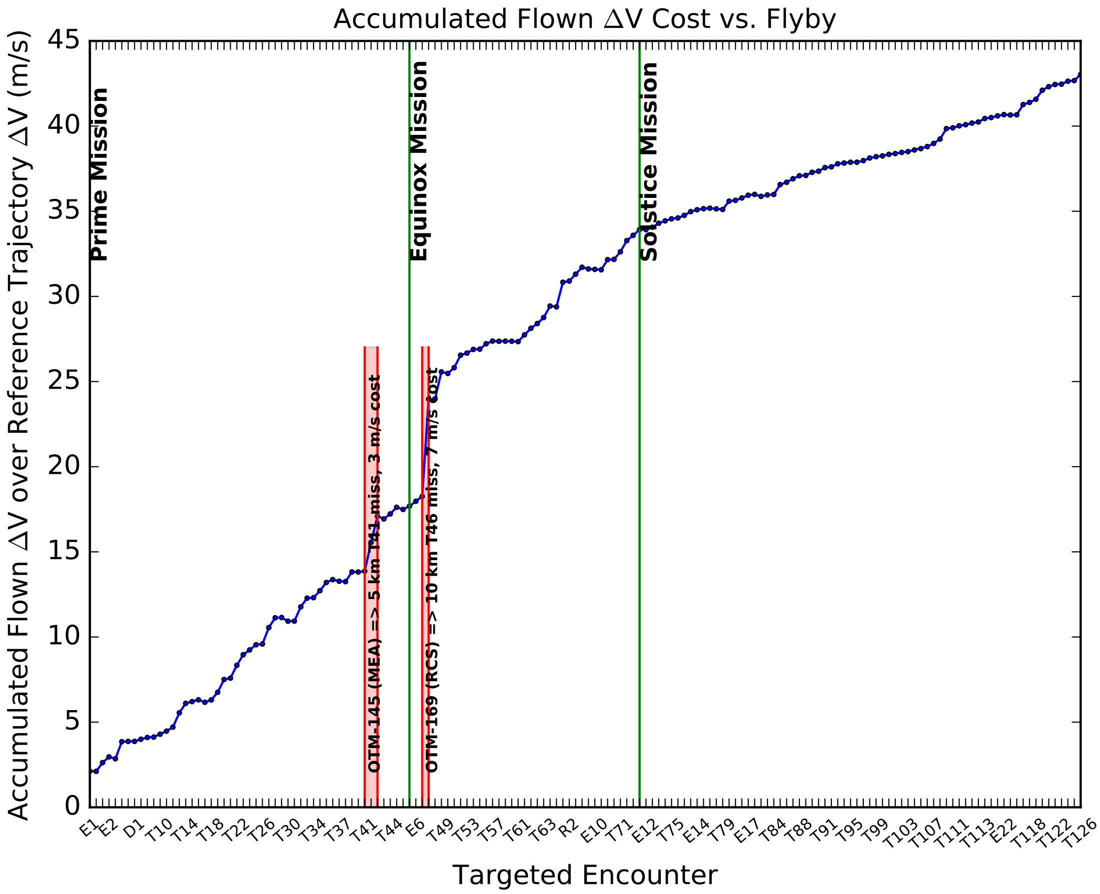


Figure 14: Accumulated Navigation Cost for Cassini Mission

placed between OTM-168 and OTM-169. OTM-168a would have been a smaller maneuver to target the T46 flyby, and consequently, OTM-169 would have likely remained small.

Based on the execution errors of OTM-145, the Cassini Project decided that future final approach maneuvers to an encounter would not be performed as small main engine burns. Due to the degraded performance of OTM-169, this project decision was extended to include large RCS maneuvers at the final approach opportunity. To help mitigate the potential of future approach maneuvers becoming large and repeating the past experience of OTM-145 and OTM-169, a maneuver was added to four different encounter spans in the Solstice Mission to provide two statistical approach maneuver opportunities (four maneuvers in total versus the nominal three maneuvers per encounter).[17] These four extra maneuvers were OTM-261a (to Titan-72), OTM-288a (to Titan-78), OTM-300a (to Dione-3/Titan-79), and OTM-312a (to Enceladus-17). Based on further analysis after the Solstice Mission began, another auxiliary maneuver OTM-468a was added prior to OTM-469 for the T126 flyby as discussed in this paper. By excluding the T41 and T46 ΔV costs, the average navigation cost per flyby in the Prime Mission reduces to 0.28 m/s and the Equinox Mission to 0.26 m/s, both closer to the 0.135 m/s average flyby cost of the Solstice Mission.

Exactly 360 maneuvers have been performed since Cassini launched in October 1997. Analysis of this large data set has been used over the years to remove observed fixed and proportional magnitude biases seen in the maneuver executions and to fine-tune the execution-error models for the main engine and RCS maneuvers.[20–22]

CONCLUSION

For nearly 20 years in flight the Cassini spacecraft has performed remarkably, returning high-value science measurements and beautiful images of Saturn, its rings, and its moons. The Grand Finale presented a unique opportunity for scientists to study Saturn from within a 2,550 km wide gap between Saturn's cloud-tops and the inner-most D-ring. Although the mission ends when Cassini plunges into Saturn's atmosphere on September 15, 2017, there will be many years ahead to study the massive amount of science that the mission has yielded about the Saturnian system. This mission has also been fruitful from a maneuver design perspective; over 500 maneuvers were planned and exactly 360 maneuvers were executed through July 2017, an ample data set to actually establish statistical models of the maneuver execution errors. Each mission phase yielded its own set of challenges: interplanetary cruise with its deep space maneuver between the Venus-1 and Venus-2 flybys, the Saturn orbit insertion maneuver in July 2004 which began a four-year Prime Mission which also saw the deployment of the Huygens probe onto the surface of Titan, the two-year Equinox Mission beginning in September 2008 with its many close Enceladus flybys, and finally the seven-year Solstice Mission in September 2010 which culminated in the Grand Finale in 2017.

Cassini is only one of two flagship-class missions, the other being Galileo, to orbit an outer planet with many satellite flybys over a long period of time. The experiences of the Cassini Maneuver Team, captured in many papers over the past two decades, will prove to be a great resource for future missions to the outer planets.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors wish to thank Duane Roth, Cliff Helfrich, and Premkumar Menon for reviewing this paper and providing valuable feedback.

APPENDIX: ADDITIONAL MANEUVER DATA

Table 15 lists additional information about each maneuver. Roll and yaw angles are the angles through which the spacecraft turns to get from an Earth-pointed orientation to the burn attitude. Central angle is the total angle swept out between the time of the maneuver and the target. Table 16 shows the corresponding times for the prime and backup maneuver opportunities.

Table 15: Maneuver Designs (OTMs 467–472). *Data from executed maneuvers are shaded in blue, and data from main engine maneuver designs are indicated in bold.*

OTM	Prime Maneuver Window					Backup Maneuver Window				
	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)
467	**−41.49**	**7049.37**	**0.9935**	**83.41**	**−103.49**	**124.32**	**6883.44**	**2.9436**	**102.78**	**−153.80**
468	−163.81	6091.47	0.2265	−121.61	−102.88	−146.58	6074.31	0.1828	−146.47	−113.23
468a	151.06	2897.61	0.1962	−41.91	−164.18	178.86	2869.63	0.4545	−80.20	−86.65
469	−145.74	314.93	0.0595	−79.48	−117.73	−100.12	269.27	0.0911	−77.89	−154.26
470	−168.34	992.97	0.1556	−174.62	−86.36	−163.27	987.90	0.1822	−174.48	−86.05
471	166.51	3535.23	0.0201	177.37	−114.06	−160.01	3501.81	0.0200	−153.10	−89.83
472	176.16	1008.36	0.1447	172.98	−136.58	−170.03	994.55	0.1440	−9.31	−37.53

Table 16: Prime and Backup Maneuver Times

	Burn Start Epoch (UTC SCET)	
	Prime	Backup
OTM-466	27-Nov-2016 16:15:00	28-Nov-2016 01:15:00
OTM-467	04-Dec-2016 11:58:00	05-Dec-2016 01:13:00
OTM-468	24-Dec-2016 00:58:00	25-Dec-2016 00:58:00
OTM-468a	22-Feb-2017 15:49:00	24-Feb-2017 21:34:00
OTM-469	18-Apr-2017 18:12:00	19-Apr-2017 12:11:00
OTM-470	24-Apr-2017 17:52:00	25-Apr-2017 06:02:00
OTM-471	10-May-2017 16:58:00	14-May-2017 18:15:00
OTM-472	15-Jul-2017 12:21:00	17-Jul-2017 12:06:00

REFERENCES

[1] B. Buffington, J. Smith, A. Petropoulos, F. Pelletier, and J. Jones, "Proposed End-of-Mission for the Cassini Spacecraft: Inner D Ring Ballistic Saturn Impact," *61st International Astronautical Congress*, Prague, CZ, 2010.

[2] T. D. Goodson, D. L. Gray, Y. Hahn, and F. Peralta, "Cassini Maneuver Experience: Launch and Early Cruise," *AIAA Guidance, Navigation, & Control Conference,* AIAA Paper 98-4224, Boston, MA, August 10–12, 1998.

[3] T. D. Goodson, D. L. Gray, Y. Hahn, and F. Peralta, "Cassini Maneuver Experience: Finishing Inner Cruise," *AAS/AIAA Space Flight Mechanics Meeting,* AAS Paper 00-167, Clearwater, FL, January 23–26, 2000.

[4] T. D. Goodson, B. B. Buffington, Y. Hahn, N. J. Strange, S. V. Wagner, and M. C. Wong, "Cassini-Huygens Maneuver Experience: Cruise and Arrival at Saturn," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 05-286, Lake Tahoe, CA, August 7–11, 2005.

[5] S. V. Wagner, B. B. Buffington, T. D. Goodson, Y. Hahn, N. J. Strange, and M. C. Wong, "Cassini-Huygens Maneuver Experience: First Year of Saturn Tour," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 05-287, Lake Tahoe, CA, August 7–11, 2005.

[6] S. V. Wagner, E. M. Gist, T. D. Goodson, Y. Hahn, P. W. Stumpf, and P. N. Williams, "Cassini-Huygens Maneuver Experience: Second Year of Saturn Tour," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2006-6663, Keystone, CO, August 21–24, 2006.

[7] P. N. Williams, E. M. Gist, T. D. Goodson, Y. Hahn, P. W. Stumpf, and S. V. Wagner, "Cassini-Huygens Maneuver Experience: Third Year of Saturn Tour," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 07-254, Mackinac Island, MI, August 19–23, 2007.

[8] T. D. Goodson, C. G. Ballard, E. M. Gist, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini Maneuver Experience: Ending the Prime Mission," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2008-6751, Honolulu, HI, August 18–21, 2008.

[9] E. M. Gist, C. G. Ballard, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini-Huygens Maneuver Experience: First Year of the Equinox Mission," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 09-349, Pittsburgh, PA, August 9–13, 2009.

[10] C. G. Ballard, J. Arrieta, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini Maneuver Experience: Ending the Equinox Mission," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2010-8257, Toronto, Canada, August 2–5, 2010.

[11] S. V. Wagner, J. Arrieta, C. G. Ballard, Y. Hahn, P. W. Stumpf, and P. N. Valerino, "Cassini Solstice Mission Maneuver Experience: Year One," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 11-528, Girdwood, AK, July 31–August 4, 2011.

[12] J. Arrieta, C. G. Ballard, Y. Hahn, P. W. Stumpf, P. N. Valerino, and S. V. Wagner, "Cassini Solstice Mission Maneuver Experience: Year Two," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2012-4433, Minneapolis, MN, August 13–16, 2012.

[13] S. V. Wagner, J. Arrieta, Y. Hahn, P. W. Stumpf, P. N. Valerino, and M. C. Wong, "Cassini Solstice Mission Maneuver Experience: Year Three," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 13-717, Hilton Head, SC, August 11–15, 2013.

[14] M. Vaquero, Y. Hahn, P. Stumpf, P. Valerino, S. Wagner, and M. Wong, "Cassini Maneuver Experience for the Fourth Year of the Solstice Mission," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2014-4348, San Diego, CA, August 4–7, 2014.

[15] S. Hernandez, S. V. Wagner, M. Vaquero, Y. Hahn, P. N. Valerino, F. E. Laipert, M. C. Wong, and P. W. Stumpf, "Cassini Maneuver Experience Through the Last Icy Satellite Targeted Flybys of the Mission," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 16-243, Napa, CA, February 14–18, 2016.

[16] F. E. Laipert, S. V. Wagner, M. Vaquero, Y. Hahn, S. Hernandez, P. N. Valerino, and M. C. Wong, "What Goes Up Must Come Down: Cassini Maneuver Experience During the Inclination-Raising Phase Prior to End of Mission," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 17-283, San Antonio, TX, February 5–9, 2017.

[17] "Cassini Solstice Mission Navigation Plan," Tech. Rep. 699-101 Update, JPL D-11621, NASA Jet Propulsion Laboratory, Pasadena, CA, February 3, 2010.

[18] M. Wong, Y. Hahn, D. Roth, and M. Vaquero, "Trajectory Dispersion Control for the Cassini Grand Finale Mission," *25th International Symposium on Space Flight Dynamics*, Munich, Germany, October 19–23, 2015.

[19] M. Vaquero, Y. Hahn, D. Roth, and M. Wong, "A Linear Analysis for the Flight Path Control of the Cassini Grand Finale Orbits," *26th International Symposium on Space Flight Dynamics*, Matsuyama, Japan, June 3–9, 2017.

[20] S. V. Wagner and T. D. Goodson, "Execution-Error Modeling and Analysis of the Cassini-Huygens Spacecraft Through 2007," *AAS/AIAA Space Flight Mechanics Meeting,* AAS Paper 08-113, Galveston, TX, January 27–31, 2008.

[21] S. V. Wagner, "Maneuver Performance Assessment of the Cassini Spacecraft Through Execution-Error Modeling and Analysis," *AAS/AIAA Space Flight Mechanics Meeting,* AAS Paper 14-390, Santa Fe, New Mexico, January 26–30, 2014.

[22] S. V. Wagner, "Cassini Maneuver Performance Assessment and Execution-Error Modeling Through 2015," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 16-305, Napa, CA, February 14–18, 2016.